Thermal Energy Storage in Building Integrated Thermal Systems: A review. Part 1. Active storage systems

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Abstract

Energy consumed by heating, ventilation and air conditioning systems (HVAC) in buildings represents an important part of the global energy consumed in Europe. Thermal energy storage is considered as a promising technology to improve the energy efficiency of these systems, and if incorporated in the building envelope the energy demand can be reduced. Many studies are on applications of thermal energy storage in buildings, but few consider their integration in the building. The inclusion of thermal storage in a functional and constructive way could promote these systems in the commercial and residential building sector, as well as providing user-friendly tools to architects and engineers to help implementation at the design stage. The aim of this paper is to review and identify thermal storage building integrated systems and to classify them depending on the location of the thermal storage system.

Keywords: thermal energy storage (TES), building integration, active system, phase change materials (PCM), thermal mass

1. Introduction

Thermal energy storage (TES) is one of the most promising technologies in order to enhance the efficiency of renewable energy sources. TES overcomes any mismatch between energy generation and use in terms of time, temperature, power or site [1]. Solar applications, including those in buildings, require storage of thermal energy for periods ranging from very short duration (in minutes or hours) to seasonal storage. The main advantage of using TES in solar systems for buildings is the success of converting an intermittent energy source in meeting the demand, which may be intermittent and/or have a time shift [2]. TES can also be used for free-cooling of buildings. The advantage here is the use of a natural resource for air conditioning in buildings.

Advantages of using TES in an energy system are the increase of the overall efficiency and reliability, but it can also lead to better economic feasibility, reducing investment and running costs, and less pollution of the environment and less CO_2 emissions [3]. Thermal energy can be stored using different methods: sensible heat, latent heat and thermochemical energy storage [1,2,3].

Sensible storage is the most common method of heat and cold storage. Here energy is stored by changing the temperature of a storage medium (such as water, air, oil, rock beds, bricks, concrete, or sand). The amount of energy stored (Eq. 1) is proportional to the temperature difference, the mass of the storage medium, and its heat capacity:

$$Q = m \cdot Cp \cdot \Delta T \qquad \text{(Eq. 1)}$$

where Cp is the specific heat of the storage material (J/kg·°C), ΔT the temperature gradient (°C), m the mass of storage material (kg).

Latent heat storage is when a material stores heat through a phase transition. Usually the solid-liquid phase change is used because of its high enthalpy and lack of pressure problems. Upon melting, as heat is transferred to the storage material, the material maintains a constant temperature constant at the melting temperature, also called phase change temperature. The amount of heat stored can be calculated by Eq. 2.

$$Q = m \cdot \Delta h \quad \text{(Eq. 2)}$$

where Δh is the phase change enthalpy, also called as melting enthalpy or heat of fusion, and m is the mass of storage material.

Any chemical reaction with high heat of reaction can be used for TES if the products of the reaction can be stored and if the heat stored during the reaction can be released when the reverse reaction takes place. The energy density during chemical changes is relatively higher than for a physical change such as phase change. For chemical reactions it is important to find the appropriate reversible chemical reaction for the temperature range of the energy source [4,5]. Also sorption systems (adsorption on solid materials or absorption in liquids) are used in thermochemical energy storage. Adsorption means binding of a gaseous or liquid phase of a component on the inner surface of a porous material. During the desorption step, the sample is heated. The adsorbed component is removed from the inner surface. As soon as the reverse reaction (adsorption) is started, the heat will be released. The adsorption step represents the discharging process. For liquid absorbents, a similar theory could be explained.

A comparison of the energy storage densities achieved with different storage methods are shown in [1], and a comparison of different storage methods for solar space heating and hot water production applications is summarized in Table 2 [6].

Table 1. Comparison of storage densities of different TES methods [adapted from 1].

	$MJ \cdot m^{-3}$	$kJ \cdot kg^{-1}$	Comments
Sensible heat			
Granite	50	17	ΔT = 20 ºC
Water	84	84	ΔT = 20 ºC
Latent heat of melting			
Water	306	330	$T_{melting}$ = 0 ºC
Paraffins	180	200	$T_{melting}$ = 5-130 ºC
salt hydrates	300	200	$T_{melting}$ = 5-130 ºC
Salts	600 – 1500	300 – 700	$T_{melting}$ = 300-800 ºC
Latent heat of evaporation			
Water	2452	2450	Ambient conditions
Heat of chemical reaction			
H_2 gas (oxidation)	11	120000	300 K, 1 bar
H_2 gas (oxidation)	2160	120000	300 K, 200 bar
H_2 liquid (oxidation)	8400	120000	20 K, 1 bar
fossil gas	32	-	300 K, 1 bar (Diekmann et al. 1997)
gasoline (petroleum)	33000	43200	(Diekmann et al. 1997)

Table 2. Comparison of different storage techniques for solar space heating and hot water production applications [adapted from 6].

		Sensible heat storage		Latent heat storage
		Water	**Rock**	**PCM**
Physical properties	Temperature range	Limited (0-100ºC)	Large	Large (depending on the material choice)
	Specific heat	High	Low	Medium
	Thermal conductivity	Low, convection effect improve the heat transfer rate	Low	Very low
	Thermal storage capacity	Low	Low	High
	Thermal cycling stability	Good	Good	Insufficient data
Economic aspects	Availability	Excellent availability	Good availability	Dependent on the material choice
	Material cost	Inexpensive	Inexpensive	Expensive
Heat transfer enhancement	Required geometry	Simple	Simple	Complex
	Temperature difference required	Large	Large	Small
	Thermal stratification effect	Present works positively	Present works positively	Generally not present with proper material choice
	Simultaneous charge & discharge	Possible	Not possible	Possible with appropriate heat exchanger selection
Application	Integration with solar heating/cooling systems	Direct with water systems	Direct with air systems	Indirect
	Corrosion with construction materials	Need corrosion inhibitors	Noncorrosive	Dependent on the material choice
	Lifetime	Long	Long	Short

Storage concepts have been classified as active or passive systems [7]. An active storage system is mainly characterized by forced convection heat transfer, and mass transfer in some cases. This may be into the storage material or with the storage medium itself circulating through a heat exchanger (the heat exchanger can also be a solar receiver or a steam generator). Such systems use one or two tanks as the storage media. Active systems are subdivided into direct and indirect systems. In a direct system, the heat transfer fluid (HTF) serves also as the storage medium, while in an indirect system, a second medium is used for storing the heat. Indirect systems are generally dual-medium storage systems: the HTF passes through the storage only for charging and discharging a storage material. This classification is followed in this review. On the other hand, passive systems are charged and discharged without any mechanical input, hence using solar radiation, natural convection or temperature difference.

Energy consumed in buildings by the HVAC systems can be reduced with proper implementation of a thermal storage system. TES allows the storage of thermal energy (heat and cold) for a later use [2]. Moreover, the integration of these systems into the architecture of the buildings, in order to give resources to architects or engineers, is an issue that still has to be developed commercially. There are few studies undertaken relating to TES technologies and building integration. A classification of several studies of *building integrated thermal energy storage* is considered in this review. The aim of this paper is to review and identify thermal storage building integrated systems and to classify them depending on the location where the storage is located.

2. Building integration of thermal energy storage systems

Energy balances undertaken by IEA [8] during the last decade accounts a global final energy use of 7209 Mtoe (Million Tonnes Oil Equivalent), where almost 40% of this final energy is consumed in buildings comprising both the residential and commercial sectors. The European Union's climate and energy package of binding legislation has established a set of 20-20-20 targets, with three key objectives for 2020, which includes a 20% reduction of greenhouse gases, a 20% improvement in energy efficiency and a 20% share of energy consumption from renewable resources. Objectives seek to reduce greenhouse gas emissions by up to 80-95% by 2050 [9]. For this reason, energy efficiency requirements have been included in many building codes and energy standards.

Low energy and Net zero energy buildings are becoming a target in the research field, through the incorporation of solar energy systems and thermal energy storage among others. Mostly, more than one technology is needed to achieve low energy rates hence, architects and engineers have to deal with their integration during the building design. Building integration can be defined by the idea of a functional or constructive incorporation of the technology in the building structure [10]. Within this definition, passive systems or technologies such as seasonal shadings, blinds, thermal mass increase or thermal insulation, which are focused on reducing the energy demand, are widely incorporated in the building design process.

Integrated designs are required in active systems such as renewable energy facilities (i.e. photovoltaic, solar thermal) or energy efficiency HVAC systems. Many studies have been focused on improving the efficiency of these technologies by incorporating thermal energy storage systems that implies an additional storage volume [11]. Therefore, a means of integration of these technologies inside the building to promote them as an alternative to the conventional systems is needed. Heretofore, this issue has been not widely considered although some studies applied the constructive incorporation of their thermal storage systems. In this paper a classification of the thermal energy storage systems that have been integrated in the building is presented, as well as a review on the studies done so far.

Figure 1 presents different ways to integrate the thermal energy storage active system; in the core of the building (ceiling, floor, walls), in external solar facades, as a suspended ceiling, in the ventilation system, or for thermal management of building integrated photovoltaic systems. This review also considers building integration of heat storage water tanks as well as ground integrated for seasonal storage.

Nevertheless, some of these systems may cause additional problems to the building physics such as thermal bridges, air tightness or humidity issues. So, architects and engineers should pay special attention to the integration of these systems in order to achieve their maximum efficiency. On the other hand, important barriers could be found in the building sector when introducing the idea of active systems integration. Building sector is quite hermetic area where new systems are difficult to be introduced mainly because a lack of knowledge of the constructors, architects and customers [10].

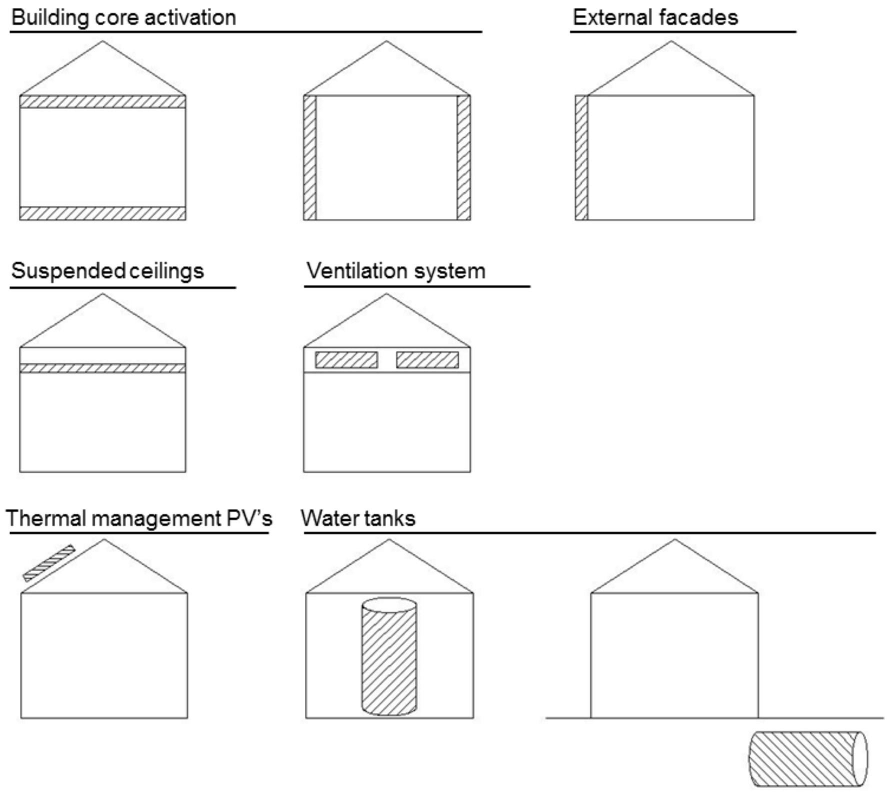


Figure 1. Thermal energy storage integration in buildings.

3. Building core activation

Building thermal inertia is commonly incorporated as a methodology to enhance the thermal performance of the construction systems using materials of high thermal mass such as bricks or concrete, which increases the thermal storage capacity of the envelope and hence attenuate thermal oscillations passively. Nowadays, the concept called thermal mass activation (TMA) is mostly used for building components with heat storage enhancement by the addition of latent heat storage materials or by the controlled management of the heat storage. In this section, building structure components such as walls, ceiling or floors used as a storage unit have been considered. In the presented studies the activation occurs inside the building component by the use of pipes or ducts.

3.1. Integration in the ceiling or floor

A ventilated concrete slab (VCS) was implemented in a nearly zero energy solar house by Chen et al [12]. The VCS was designed as a thermal storage component to store solar energy for heating purposes. The system is actively charged through a building integrated photovoltaic/thermal (BIPV/T) system located in the roof, where the air is the heat transfer fluid (Figure 2). Then, the heat stored is passively released to cover the heating demand of the building. Data registered during the commissioning of the building showed that the VCS could store from 9 to 12 kWh during a clear sunny day.

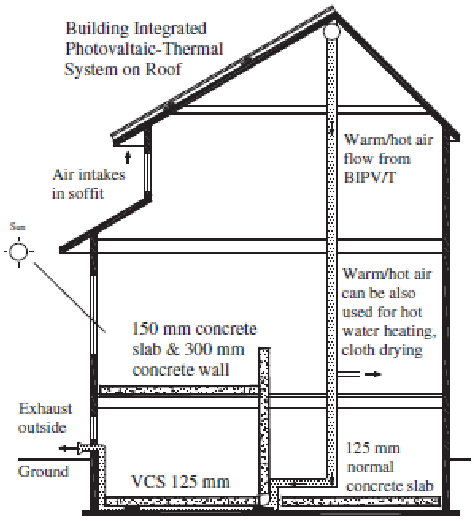


Figure 2. Scheme of the VCS linked with BIPV/T system [12]. Reprinted from, Solar Energy, 84(11), Yuxiang Chen, Khaled Galal, A.K. Athienitis, Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 2, ventilated concrete slab, 1908-19, November 2010, with permission from Elsevier.

Navarro et al [13] also designed a system where air is the heat transfer fluid. The active slab presented in this study is able to provide heating and cooling following the operating principle shown in Figure 3. Phase change materials encapsulated in aluminium tubes are placed inside the hollows of the prefabricated concrete slab with a phase change temperature of 21 ºC. During winter mode, the PCM is melted by the injection of hot air from the solar air collector and stored until a heating supply is needed. In summer, outside air is pumped to the slab at night to solidify the PCM. Moreover, night free cooling mode could be used if the inner environment has a cooling demand and the outside conditions are able to cover it. The cooling discharge is carried out by pumping interior air through the hollows of the concrete slab.

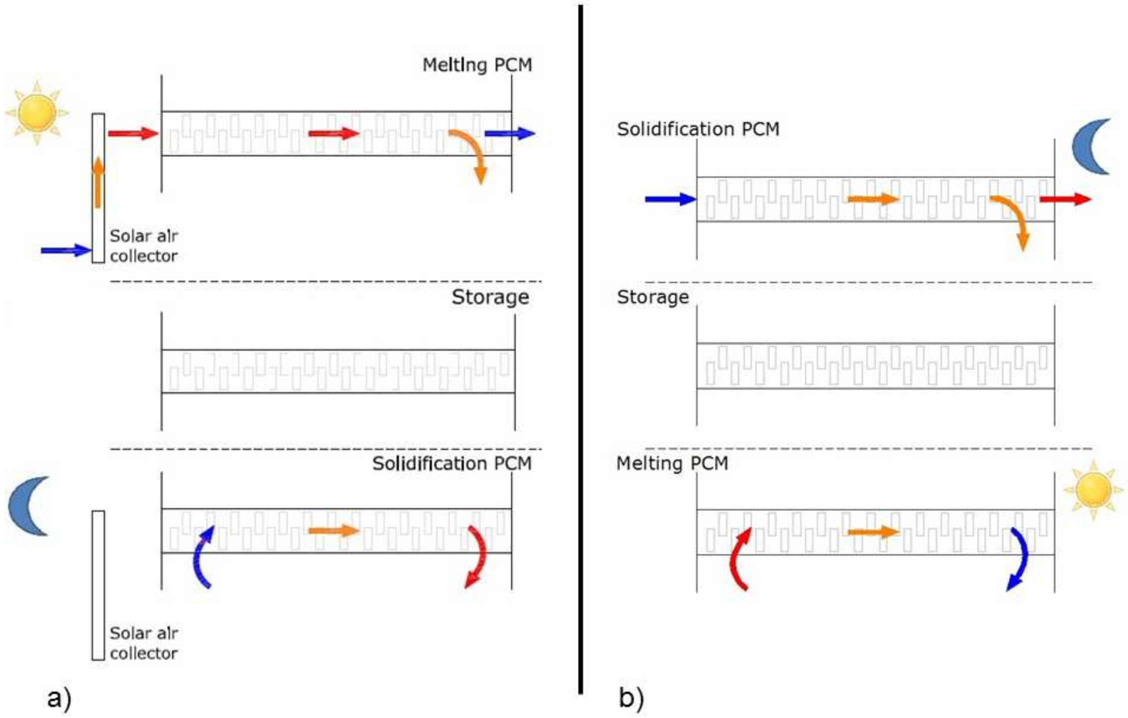


Figure 3. Operating principle Active slab scheme a) heating b) cooling [13]. Reprinted from, Energy and Buildings, 103, L. Navarro, A. De Gracia, A. Castell, S. Álvarez, L.F. Cabeza, PCM incorporation in a concrete core slab as a thermal storage and supply system: proof of concept, 70-82, September 2015, with permission from Elsevier.

TermoDeck, a commercial product, with similar properties to the previous study, consists of concrete prefabricated slab [14] with hollow cores through which air is pumped. The panel absorbs heat during the day and then at night outside air is drawn through the cores to cool down the concrete. This reduces the cooling peak load through a passive/active discharge. It has been installed in many buildings in northern Europe and United Kingdom with successful results [15].

Another method of thermal mass activation is through embedded water pipes, such as the Jin and Zhang [16] study which also included phase change materials (PCM) on the surface of the concrete slab radiant floor. The system proposed consists of two layers of PCM that have different melting temperatures (Figure 4). Each layer is used to store energy and discharge it in the peak period either for heating or cooling purposes. The water temperature circulating by the pipes during heating and cooling mode is 52 ºC and 7 ºC, respectively. For this reason, during heating PCM for cooling is completely in liquid state, while in cooling mode PCM for heating is acting as a solid. Authors found that the optimal melting temperatures for both PCM were defined numerically being

38ºC and 18 ºC for heating and cooling respectively. Moreover, the energy release when adding PCM layers is increased by 41% for heating and 38% for cooling.

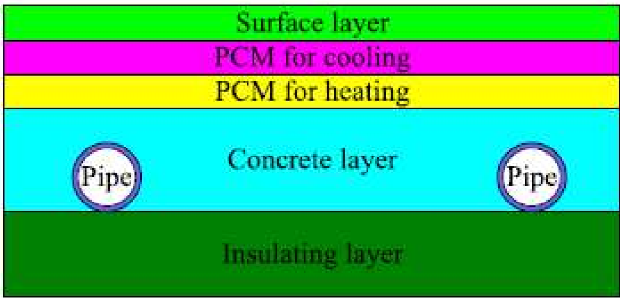


Figure 4. Scheme of the double layer PCM floor [16]. Reprinted from, Applied Thermal Engineering, 31(10), Xing Jin, Xiaosong Zhang, Thermal analysis of a double layer phase change material floor, 1576-81, July 2011, with permission from Elsevier.

Pomianowski et al [17] added a 3 cm thickness layer of PCM-concrete mixture on a Thermally Activated Building System (TABS). This system consists of a concrete component with water pipes that is currently available as a commercial product called ThermoMax [18]. The authors concluded from the simulation results that the addition of a layer of PCM concrete mixture contributes to reduced energy efficiency of the thermal activated building system. Authors attribute this effect to the drastic drop in measured thermal conductivity that they found out during their investigation on the PCM concrete material. However, the authors stated that further studies are needed on the optimization of TABS as well as the PCM-concrete mixture.

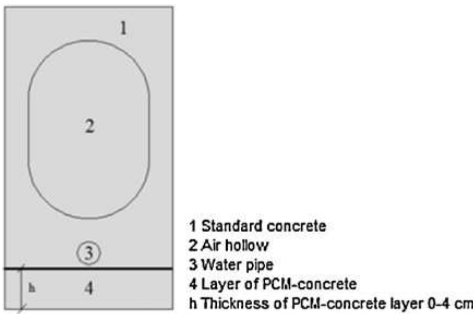


Figure 5. Concrete core deck element with PCM section [17]. Reprinted from, Energy and Buildings, 53, M. Pomianowski, P. Heiselberg, R.L. Jensen, Dynamic heat storage and cooling capacity of a concrete deck with PCM and thermally activated building system, 96-107, October 2012, with permission from Elsevier.

3.2. Integration in the wall

Fraisse et al [19] studied the integration of a solar air collector in a timber frame house and a heavy ventilated internal wall. The heat supplied by the collector is circulated through the concrete wall cavity charging the internal wall with solar energy. Several operational modes referring to the air circulation, open or closed loop, were studied with numerical simulations. In open loop the ventilation of the heavy internal wall is permanent as fresh air is always circulating, while in closed loop mode the fresh air ventilation is separated from the system. The authors conclude that the closed loop (Figure 6) integrated collector with the heavy internal wall is much more efficient due to its independence from the ventilation system.

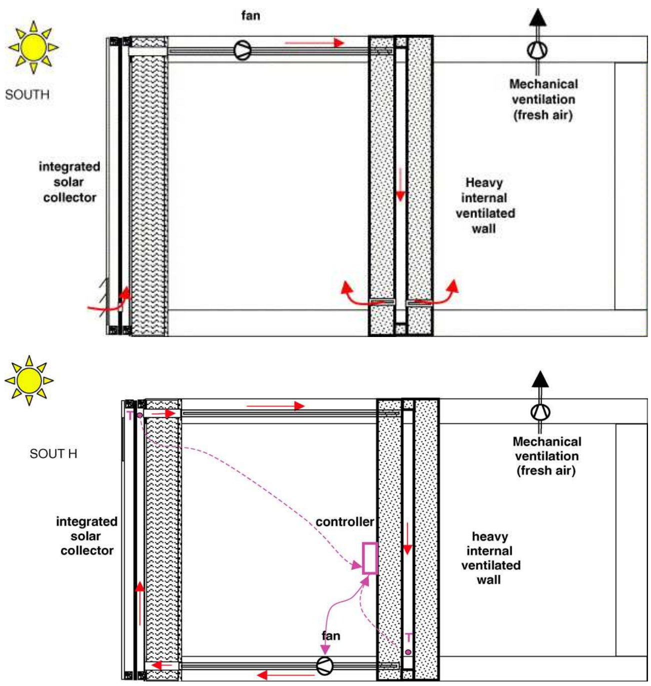


Figure 6. Diagram of open loop (up), closed loop (down) mode in winter [19]. Reprinted from, Energy and Buildings, 38(4), G. Fraisse, K. Johannes, V. Trillat-Berdal, G. Achard, The use of a heavy internal wall with a ventilated air gap to store solar energy and improve summer comfort in timber frame houses, 293-302, April 2006, with permission from Elsevier.

Wall activation systems presented the inconvenient of being usually exposed and wall surfaces are usually used for shelving, cupboards, or other furniture. For this reason, ceiling and floor activation components is considered more convenient in most cases.

Building core activation is demonstrated to be an interesting technology for new constructions domestic, public or office buildings.

4. Integration in suspended ceilings

Nowadays, a significant amount of old buildings need an energetic retrofitting in order to accomplish the standards defined by the European directives [20]. For this reason, the implementation of thermal energy storage components in the suspended ceiling such as actively charged water panels are good options as cooling or heating systems.

Roulet et al [21] presented the design of radiant panels filled with water used for cooling and heating. The panels are made of stainless steel and the water inside them is directly in contact with 98% of the panel surface. Although radiant ceilings are mostly used for cooling, these radiant panels are designed also for heating with low temperature sources, such as heat pumps or active solar systems. Depending on the building requirements radiant panels could be placed on the ceiling or on the walls and in some cases it could be an efficient solution to control the indoor temperature.

A new thermally activated ceiling panel based on gypsum with microencapsulated PCM was presented by Koschenz and Lehmann [22]. The study presented the panel as an alternative for the building refurbishment, hence the authors focused on minimizing the panel thickness as well as providing good storage capacity. A capillary water tube system is installed inside the gypsum panel to actively control the thermal mass (Figure 7). The system is designed to absorb the thermal loads of office buildings during day time and then cooled down by means of the water pipe system. Simulation studies and laboratory tests were carried out for buildings with high thermal loads and high solar gains, and also for a later implementation in Limburgerhof, Germany. Authors determined that a 5 cm layer gypsum panel with 25% of PCM by weight was adequate to maintain a comfortable room temperature in glazed facade office buildings.

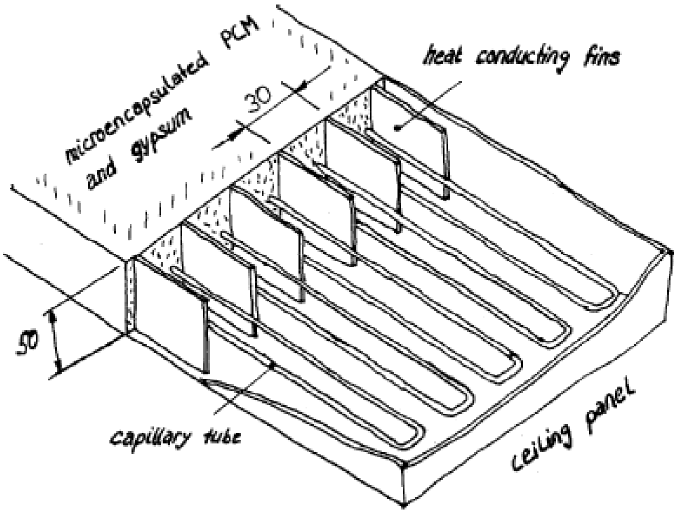


Figure 7. Thermal activated ceiling panel scheme [22]. Reprinted from, Energy and Buildings, 38(4), M. Koschenz, B. Lehmann, Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings, 567-78, June 2004, with permission from Elsevier.

Suspended ceiling products presented in this section, such as radiant panels or thermal activated gypsum panels, which were experimentally tested with successful results, are some solutions for building energetic refurbishment.

Old buildings need retrofitting to accomplish the new energy efficiency standards so implementation of energy saving actions must be undertaken.

5. Integration in the ventilation system

Thermal storage units could be also placed in the ventilation duct systems behind the suspended ceiling, in the heat recovery unit or the air handling unit, as a thermal battery taking advantage of the night ventilation mostly for cooling purposes.

5.1. Pipes/ducts

Turnpenny et al. [23,24] presented the prototype testing of a latent heat storage unit which incorporates pipes embedded in PCM. The authors demonstrated that the system proposed has substantial cost and energy saving benefits in reducing overheating in UK summer conditions compared to a conventional system. During the day the PCM-pipes located under the ceiling absorbs the heat loads of the room. Then, the system takes advantage from the night ventilation in order to freeze the PCM through a fan installed above the PCM-pipes (Figure 8). The field tests suggested that the system was practically and technically the most attractive alternative to air-conditioning and was suitable for retrofitting to buildings [25]. This research led to the development of Monodraught's Cool-Phase.

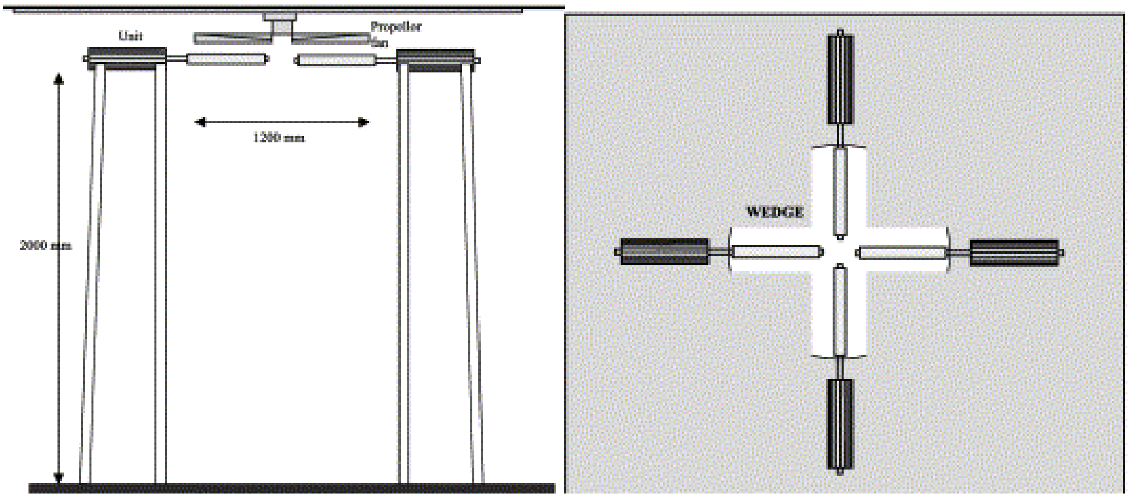


Figure 8. PCM/pipe system side views (right) plan view of four units, showing wedges to block air flow between pipes (left) [23,24]. Reprinted from, Applied Thermal Engineering, 21(12), J.R. Turnpenny, D.W. Etheridge, D.A. Reay, Novel ventilation system for reducing air conditioning in buildings. Part II: testing of prototype, 1203-17, August 2001, with permission from Elsevier.

In 2002 the refurbishment of a UK office building led consultants Faber Maunsell to work with Climator to develop a system of PCM 'pouches' that is now called Cooldeck. These pouches were inserted into the air-conditioning ducts. During the day air circulating through the ductwork was cooled by the pouches while night-time air was used to recharge them for the following day [26].

A PCM packed bed incorporated in the air ducts of the ventilation system was developed by Yanbing et al [27]. As Figure 9 describes, the PCM is charged during night-time with outside air storing cool energy between 22 ºC and 26 ºC in order to meet the cooling load demand during daytime. Experimental results were used to validate the numerical model developed by the authors, as well as to demonstrate an indoor temperature reduction with the PCM packed bed system compared to a conventional one.

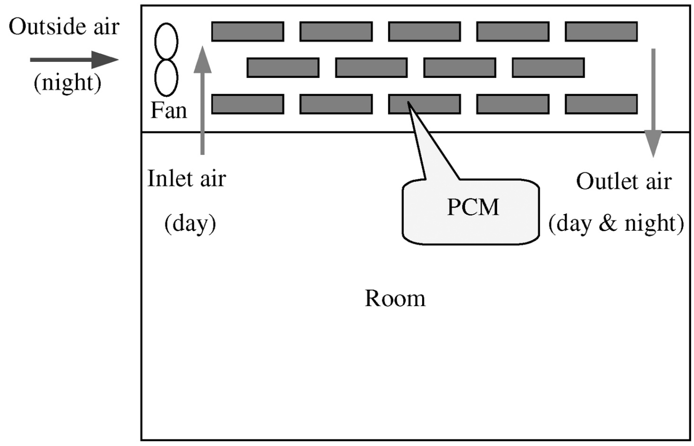


Figure 9. Natural ventilation with PCM packed bed system [27]. Reprinted from, Energy and Buildings, 35(4), Kang Yanbing,Jiang Yi,Zhang Yinping, Modeling and experimental study on an innovative passive cooling system—NVP system, 417-25, May 2003, with permission from Elsevier.

An experimental investigation of a PCM free-cooling system is presented by Stritih and Butala [28]. The cold storage system consists of a metal box with aluminium fins filled with PCM paraffin which is designed to be located in an air duct installation. The operational principle is based on taking advantage of the night temperatures to solidify the PCM, while the air is pumped through the storage unit during the daytime when a cooling supply is needed (Figure 10).

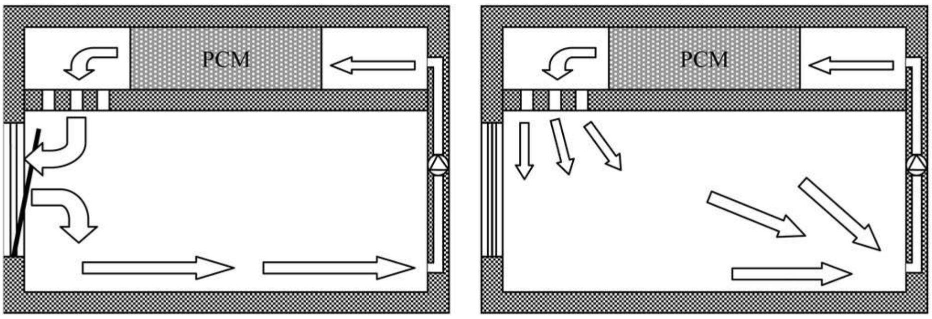


Figure 10. Operational principle of PCM free-cooling system [28]. Reprinted from, International Journal of Refrigeration, 33(8), U. Stritih,V. Butala, Experimental investigation of energy saving in buildings with PCM cold storage, 1676-83, December 2010, with permission from Elsevier.

5.2. Air handling unit (AHU)

The Cool-Phase is a cooling and ventilation system designed and commercialized by the Monodraught Ltd Company (UK) which contains an air handling unit (AHU) and a thermal battery of PCM macroencapsulated in metallic panels [29]. The system is designed to operate in the summer period in the following sequence; at night, the outer air is used to cool down the room and at the same time passed through the thermal battery to solidify the PCM. During the daytime, when the internal temperature rises, room air is recirculated through the thermal battery covering the cooling demand and preventing overheating in office buildings absorbing the heat gains. Some case studies were monitored from January 2013 to September 2013, showing the internal temperature evolution which remained under 25 ºC throughout the test period and with an average temperature of 22.7 ºC.

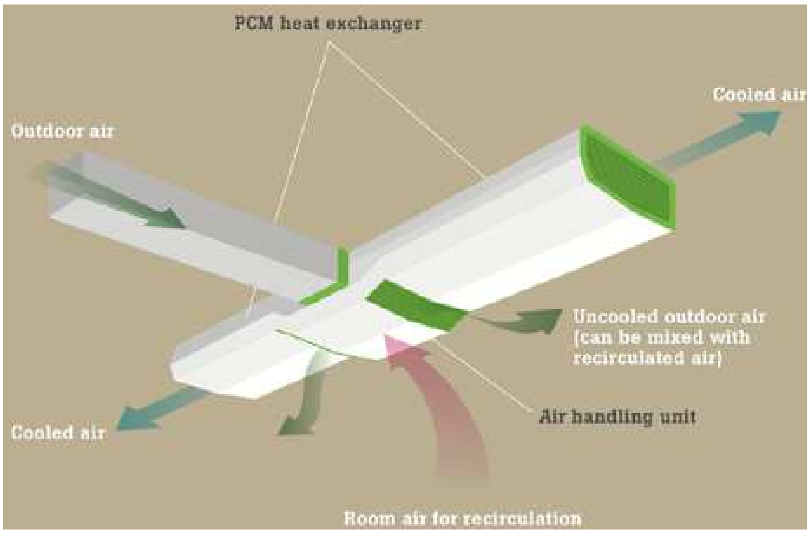


Figure 11. Air flows overview of the Cool-Phase system [29].

Addition of thermal storage units in ventilation systems either air ducts or air handling units are interesting locations for building retrofitting due to its implementation rather than the core activation systems. Commercial systems such as Cooldeck or Coolphase which incorporate phase change materials in the AHU are currently marketed for use and tested in some buildings.

6. Integration in an external solar facade

Double skin facades (DSF) have become a characteristic of modern buildings mainly because of the aesthetic value and the daylight contribution. Moreover, double skin facades if well designed are able to improve the thermal energy performance of the building [30]. DSF have high potential in reducing energy consumption of the HVAC systems, nevertheless some problems need to be overcome such as the overheating in summer. The incorporation of thermal energy storage system in DSF has been studied using both sensible and latent methods.

6.1. Using sensible heat storage

Fallahi et al. [31] discussed the integration of thermal mass into a DSF in order to reduce the risk of overheating and increase the system efficiency in both winter and summer periods. Three alternatives of concrete thermal mass combinations with DSF were studied (Figure 12) with mechanical and natural ventilation alternatives. A numerical model was developed to demonstrate that the use of thermal mass in the air channel with mechanical ventilation enhances the energy savings from 21% to 26% in summer and from 41% to 59% during winter. On the other hand, energy savings achieved with naturally ventilated DSFs were found to be negligible year-round.

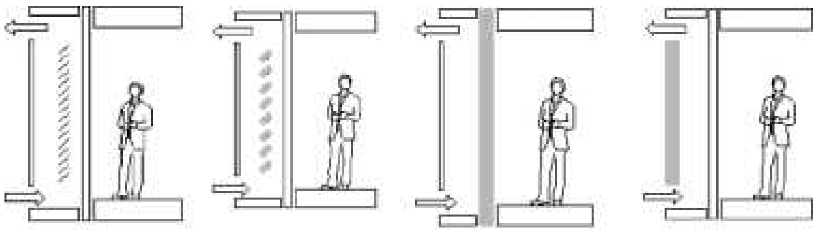


Figure 12. (A) Conventional DSF with venetian blind, (B) proposed DSF combined with concrete thermal mass (replacement with shading device), (C) proposed DSF combined with concrete thermal mass (replacement with inner pane), (D) proposed DSF combined with concrete thermal mass (replacement with outer pane) [31]. Reprinted from, Energy and Buildings, 42(9), A. Fallahi, F. Haghighat, H. Elsadi, Energy performance assessment of double-skin façade with thermal mass, 1499-1509, September 2010, with permission from Elsevier.

6.2. Using latent heat storage

Costa et al. [32] developed eight prototypes to evaluate experimentally the thermal performance of VDSF with mechanical ventilation in different European climates (Southern, Central and Northern climates). In one prototype (M3) a PCM layer was included in the inner skin; however, due to the small amount of PCM (4 cm), no significant improvements were found due to its use (Figure 13).

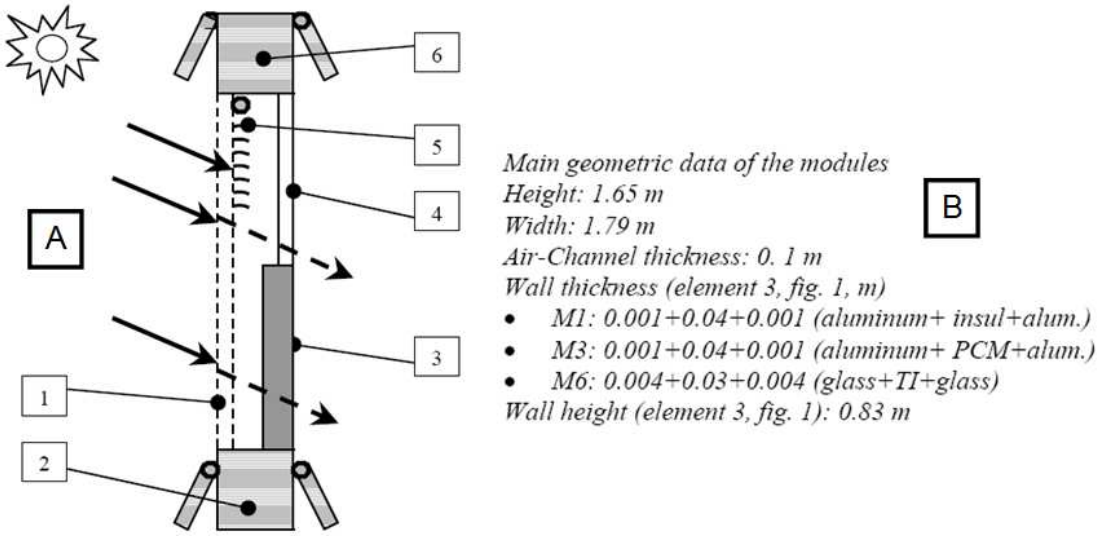


Figure 13. (A) South prototypes sketch. 1 outdoor glass, 2 lower damper box & ventilators, 3 indoor wall, 4 double indoor glass, 5 blind, 6 upper damper box. (B) Main geometric data of the modules (M1, M3 and M6) [32].

De Gracia et al. [33] tested experimentally the thermal performance of a ventilated facade with macro-encapsulated PCM in its air chamber under mechanical and natural ventilation. During the heating season the facade acts as a solar collector during the solar absorption period (Figure 14). Once the PCM is melted and the solar energy is needed by the heating demand, the heat discharge period starts. This discharge period is performed until no more thermal energy is needed or can be provided by the system. The authors registered a reduction of the 20% in the electrical energy consumption of the installed HVAC systems because of the use of this solar ventilated facade.

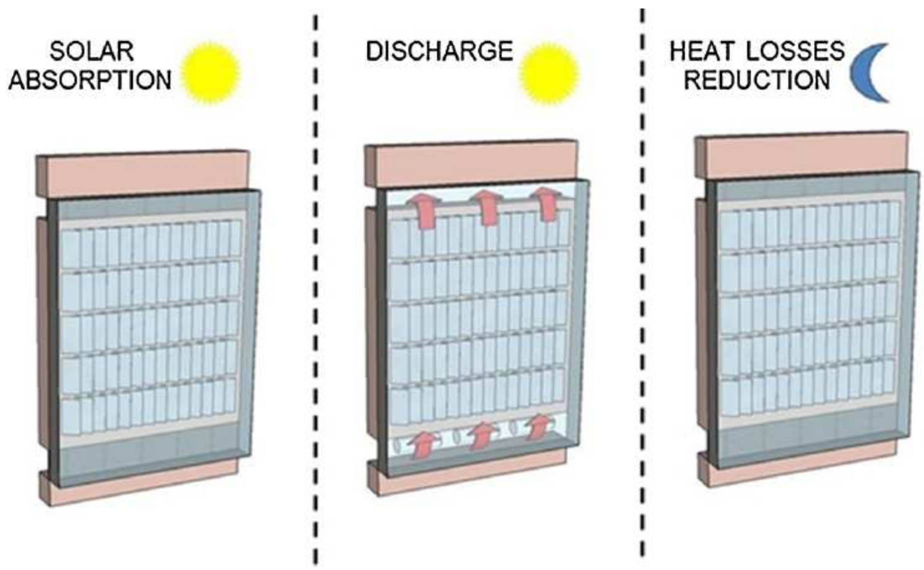


Figure 14. Operational mode of the system during winter [33]. Reprinted from, Energy and Buildings, 58, A. de Gracia, L. Navarro, A. Castell, A. Ruiz-Pardo, S. Alvárez, L.F. Cabeza, Experimental study of a ventilated facade with PCM during winter period, 324-32, March 2013, with permission from Elsevier.

Diarce et al. [34] investigated numerically and experimentally the thermal performance of an active ventilated facade with PCM in its outer layer. The behaviour of this system was compared against traditional construction systems. It was shown that the PCM led to a significant increase in the heat absorption during the phase change thermal range. It was also demonstrated that the thermal inertia of the ventilated facade with PCM was higher than that of the different evaluated traditional systems.

Office and public buildings have huge potential on implementing thermal energy storage in double skin facades for either heating or cooling purposes as it was demonstrated in the studies presented.

7. TES integrated into solar collectors

Integrated thermal energy storage is a common aspect of thermal solar collectors used in the Mediterranean, where a store is situated close to the solar collector header or acts as the header for the collector as outlined by Smyth et al. [35]. Eames and Griffiths [36] explored, using computer simulation, the use of a phase change slurries to replace water in an integrated solar store. The advantages gained were marginal compared to water, with the retention of heat at higher temperatures having the potential to increase the solar fraction. Griffiths et al. [37] experimentally explored the concept of an integrated solar store containing phase change slurry, see figure 13. The culture and lifestyle of northern European latitudes tends to demand hot water at the beginning of the day. The proposal was to store heat collected during the previous day for use the following morning. Studies using water showed that heat losses degraded the store to be below a useable level while a phase change slurry could hold the heat if the correct concentration of encapsulated material to carrier fluid was used. However over time the slurry material disaggregates and quickly becomes unusable. Huang et al. [38] furthered the work of Griffiths et al. [37] and developed a test system to fully evaluate the performance of a phase change slurry store. The authors conclude that concentrations of 50% or above were unusable due to the low rates of heat transfer and suppressed natural convection within the liquid of the slurry.

Figure 15. Integrated Solar Thermal Collector stores utilising phase change slurries [37]. Reprinted from, International Journal of Ambient Energy, 28(2), P.W. Griffiths, M.J. Huang, M. Smyth, Improving the heat retention of integrated collector/storage solar water heaters using Phase Change Materials Slurries, 89-98, April 2007, with permission from Taylor & Francis.

8. TES for thermal management of building integrated photovoltaics

Thermal energy storage has been also implemented in building integrated photovoltaics (BIPV), in fact Norton et al. 2011 [39] stated that storage, PCM in this case, can be used for thermal management of these systems. Protecting electronic modules from excessive temperatures may be accomplished by: (i) active cooling systems, such as air-conditioning, requiring AC power and high levels of maintenance; (ii) assisted systems, such as air-to-air heat exchangers, which use DC power, but require less maintenance than the active system; (iii) maintenance free passive systems requiring no power and/or (iv) removing and storing the excess heat from the PV cells using phase change material (PCM) [39,40]. However, some recommendations should be taken into account before the integration of PCM in PV systems. The PCM should have a flash point considerably higher than the maximum operating temperature of the PV system and it should be non-flammable and non-explosive [41].

A system using a PCM to moderate the BIPV temperature rise (PV/PCM) was first investigated in 1978 by Stulz [42] who showed an increase of 1.4% in the electrical efficiency of the PV. It was noted that this could be improved with enhanced thermal conductivity of PCM. Later Huang progressing the concept independently and designed, fabricated, tested and simulated [] whereby the PCM was placed behind the PV panel and in direct contact. Small scale practical experimental tests were carried out both in the laboratory and outdoors, at PV cell scale [44,45] and later at PV module scale [46]. The validation of the numerical model was successfully done with experimental data of a prototype under real conditions. Authors concluded that the use of metal fins in PCM containers provide a more uniform temperature distribution in the PV/PCM system [43]. Different type of fins configuration were tested concluding that straight fins provide the lowest BIPV surface temperature, while the soft-iron wire matrix gave the most stable temperatures. Moreover, Huang et al. [44] demonstrated that the use of a PV/PCM system can significantly reduce the temperature rise of the PV compared to a conventional aluminium fined PV panel with natural ventilation.

Hasan et al. [47] continued this work with larger PV panels with dimensions 771 mm × 665 mm, which were integrated in an aluminium heat sink fitted internally with back to back vertical aluminium fins and filled with PCM to form a PV-PCM system (Figure 16). The system was deployed outdoors in two different climatic conditions, i.e., the cool climate of Ireland and the hot climate of Pakistan, to compare PV-PCM performance. The PCM systems maintained 10 ^{o}C and 21 ^{o}C reductions in temperature for Ireland and Pakistan respectively.

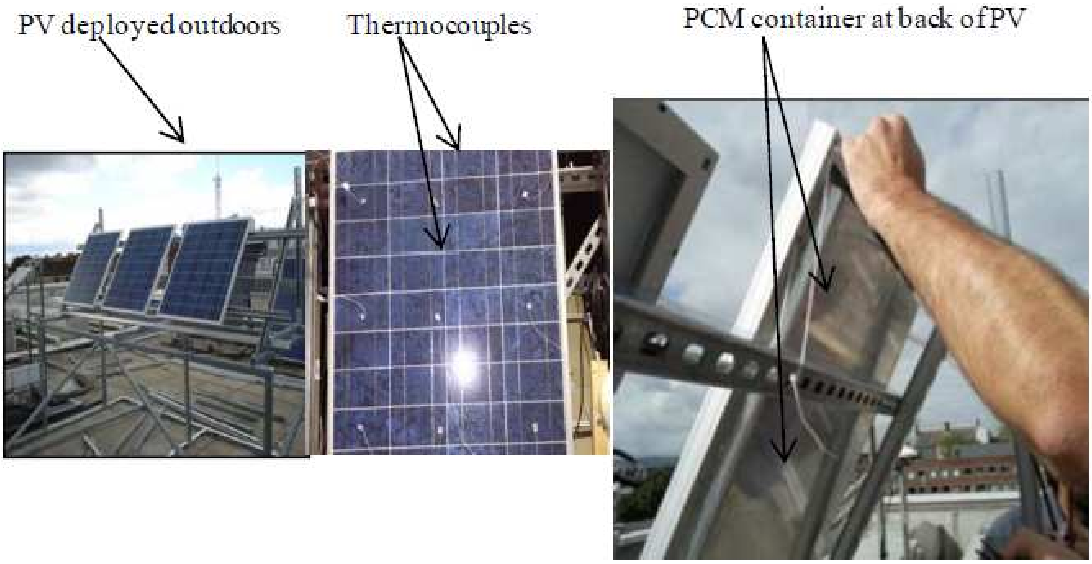
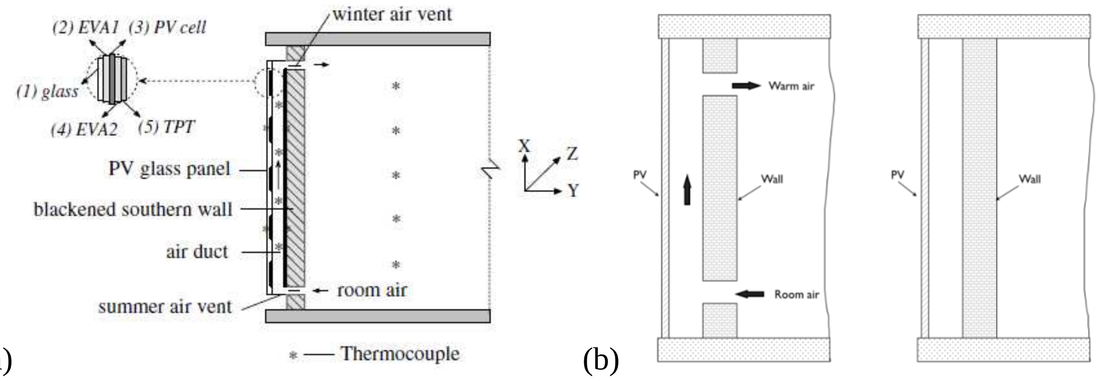


Figure 16. Experimental set-up consisting of PV deployed outdoors at latitude angle of the selected sites, thermocouples installed at PV front Surface and the PCM container integrated at the back of the PV [47].

Japs et al. [48] also undertook an experimental analysis of a PV module integrated with paraffin based PCM. The PCM was incorporated with an aluminium-polymer compound to improve its thermal properties. The PCM was shown to have a higher thermal conductivity but decreased storage capacity when compared to its non-improved counterpart. Macro-encapsulated PCM bags were attached to the back of a PV and were installed in Paderborn, Germany. It was found over a 25 day period the PCM minimized daily temperature fluctuation of the surface of the PV compared to a system without PCM and the improved PCM regulated the temperature for 5.5 hours compared to non-improved PCM.

There are also some studies that combined PV panel with the Trombe wall concept. Jie et al. [49] designed a solar heating system consisting of PV glass panel located in front of a blackened wall with an air chamber between them. Two openings located at the top and bottom of the wall allows the room air to be heated up in the air chamber through natural convection effect (Figure 17). Authors conclude that indoor temperature increase with a maximum of 7.7 °C, compared with the reference room, was registered. Nevertheless an electrical efficiency of 10.4% was obtained from the PV cells.



(a) (b)

Figure 17. (a) PV-trombe wall for solar heating [49,48] (b) BIPV/T-PCM vented and un-vented Trombe-Michel walls. Reprinted from, Applied Thermal Engineering, 27(8-9), Ji Jie, Yi Hua, Pei Gang, Lu Jianping, Study of PV-Trombe wall installed in a fenestrated room with heat storage, 1507-15, June 2007, with permission from Elsevier.

A numerical simulation of BIPV/T-PCM vented and un-vented Trombe-Michel walls, illustrated in Figure 17b, was validated via experimental results from a BIPV/T system [50]. The air cavity allows for ventilation and each system has been investigated with and without it. The results of non-ventilation showed the PCM caused a decrease of 7ºC when comparing the temperature of the air cavity this is due to the latent heat storage of the PCM. However, ventilation of the systems showed a much lower difference of 2ºC (BIPV/T-PCM 28ºC and BIPV/T 30ºC) when looking at the maximum air temperature, suggesting that heat is being removed by ventilation rather than the PCM. The investigations show that the effect of the storage in the PCM reduces the PV temperature and thus raises the PV efficiency. However, during winter conditions the storage of heat causes adverse effects as the heat transfer from air cavity to the interior of the room is reduced [50].

The systems reviewed which included the incorporation of PCM in BIPV panels where demonstrated and increase in PV performance due to the thermal management functionality of the PCM through excess heat storage. Moreover, new combinations of trombe wall system with PV cells are presented with an interesting heating potential.

9. Integration of heat storage water tanks

Thermal storage water tanks have an important role on the final efficiency of the solar system or the domestic hot water system. The main issue that has been widely discussed and studied is the heat loss caused from the mixing of cold and hot water. Therefore, these studies have been focused on the shape of the tank and the implementation of phase change materials to enhance thermal stratification [51]. However, when implementing solar thermal systems in buildings the volume of the solar water tank needs to be taken into account. Few studies found in the literature are presented on current projects of building integration water tanks.

9.1. Integrated in the building

Water tanks from solar systems have been integrated in the building in several projects. For example, in *Das Sonnenhaus* [52], a water tank has been architecturally integrated in the living area (Figure 18).

Figure 18. Solar water tank integrated in a living room [52].

In Regensburg, the first fully solar-heated solid house was built [52] (Figure 19). The total heat supply of the house is covered by a 38,500 L solar storage without additional heating.

Figure 19. Solar water tank integrated in a solar building in Regensburg [52].

One more example of a Zero Energy Building is the Nature Park Information Centre located in Germany. It has 110 m^2 of solar thermal collectors and one buffer storage of 22,000 L which cover the energy demand (Figure 20).

Figure 20. Solar water tank integrated in a zero energy house nature park information centre [52].

9.2. Ground integrated tanks for seasonal storage

Seasonal Thermal Energy Storage (STES) systems are used to store thermal energy produced by an array of solar collectors in summer months for use during the winter period [53]. A summary of the main characteristics of the main types of STES (TTES, PTES, BTES and ATES) systems is provided below. These characteristics represent the basic information for the determination of the most appropriate underground STES configuration in relation to the potential built environment constraints which can arise (due for example to densely populated urban areas compared to single dwellings in rural areas).

Types of built environments are varied. One of the main parameters used for the built environment characterization is the building density, which represents the concentration of buildings in a geographic area and is used to give an idea of the available installation space for the STES system. In addition, the main urban network constraints need to be defined and are typically divided into two categories: physical constraints (building density, archaeological constraints, urban infrastructure, public transport systems, district heating and public utilities), and environmental constraints (noise pollution, hazardous materials and nature conservation).

A key determinant factor on the use of underground thermal energy storage is that of the type of soil and rock encountered. Classification systems such as the Unified Soil Classification System and the Bieniawski rock mass rating system respectively are used to determine the principal constraints related to the underground configuration such as soil strength, presence of groundwater and boundary conditions.

Finally, consideration needs to be given to the excavation, perforation, supporting systems and shaft constructions methods to be employed. For each of these techniques, the operation process needs to be considered in addition to the deployment of appropriate machines for excavating and perforating. The supporting systems represent fundamental complementary systems to the excavation and perforation, and have to be chosen considering specific factors, such as soil conditions, protection of adjacent structures, ease of construction, environmental issues and more. In some cases trenchless systems need to be considered given that they are minimally invasive and therefore appropriate to density populated urban areas.

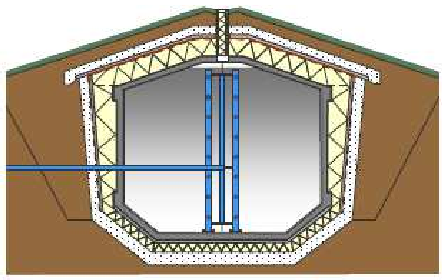
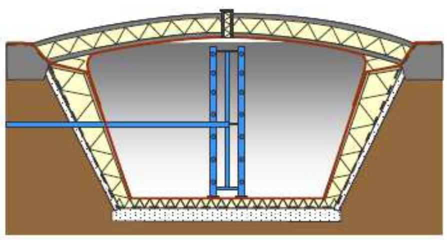
9.2.1. STES systems typologies

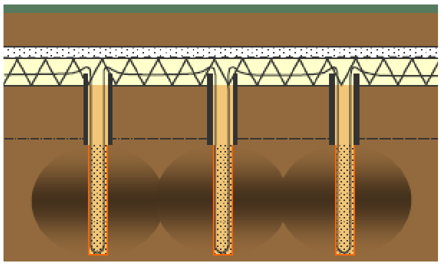
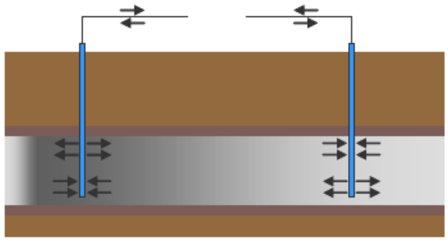
The EU funded FP 7 EINSTEIN project is researching the Effective Integration of STES in Existing Buildings where the four main types of STES have been distinguished [54,55]:

- Tank Thermal Energy Storage (TTES)
- Pit Thermal Energy Storage (PTES)
- Borehole Thermal Energy Storage (BTES)
- Aquifer Thermal Energy Storage (ATES)

A summary of the main characteristics related to physical installation aspects and energy performance of each of the types are given in Table 3.

Table 3. STES systems overview [54,55].

Tank thermal energy storage (TTES)	
• Suitable geological conditions: tank construction can be built almost independently from geological conditions, as much as possible avoiding groundwater • Depth: from 5 to 15 m • Heat storage capacity: between 60 and 80 kWh/m^3 • Tank's characteristics: **Structure** made of concrete, stainless steel or fibre reinforced polymer. A coating of polymer or stainless steel covers the inside tank surface. The outside surface has an **insulation layer** of foam glass gravel for the bottom part, and expanded glass granules in the membrane sheeting for walls and top.	
Pit thermal energy storage (PTES)	
• Suitable geological conditions: almost independent from geological conditions, as much as possible avoiding groundwater • Depth: from 5 to 15 m • Pit thermal energy storage filled with water or gravel-water mixture (gravel fraction 60-70%) • Heat storage capacity with gravel-water mixture: between 30 and 50 kWh/m^3 (equivalent to 0.5-0.77 m^3 of water)	
Borehole thermal energy storage (BTES)	

• Suitable geological formations: rock or water saturated soils with no or only very low natural groundwater flow. The ground should have high thermal capacity and impermeability. • Depth: from 30 to 100 m • Heat directly stored in the water-saturated soil: u-pipes, also called ducts, are inserted into vertical boreholes to build a huge heat exchanger. • Heat storage capacity of the ground: between 15 and 30 kWh/m^3	
Aquifer thermal energy storage (ATES)	
• Suitable geological formations: aquifer with high porosity, ground water and high hydraulic conductivity (kf > 10-4 m/s), small flow rate, up and down enclosed with leak-proof layers. • Aquifers defined as naturally occurring self-contained layers of ground water, are used for heat storage. • Heat storage capacity: between 30 and 40 kWh/m^3	

Seasonal thermal water tanks coupled to solar systems started to be popular within the last decade in central Europe countries to cover domestic hot water and heating supply. Some implemented examples are reviewed in the chapter below. The main interesting issue is the architectural integration of the huge water storage tanks. On the other hand, underground integration of seasonal thermal storage water tanks was also presented in the following section. However, seasonal water tanks integration requires lot of space so in some cases it has limited potential.

9.3. Examples of single dwelling STES

Central Continental Climate

A number of companies located in Switzerland and Germany have commercialized systems which integrate solar collectors and buffer/Seasonal Thermal Energy Storage systems in single dwellings.

Josef Jenni built a purely solar heated home in 1989 in Oberburg, Switzerland, which uses 84 m² of solar collectors in combination with 118 m³ of storage capacity in three storage tanks (92, 13, 13 m³) to heat a house of 130 m². His company, Jenni Energietechnik, supplies storage tanks for buildings that are able to cover at least 50% of the energy requirement for hot water and heating with solar energy (Figure 21) [56].

Figure 21. Swiss Solartank provided by Jenni Energietechnik [56].

The storage tanks manufactured by Jenni Energietechnik have been adopted by two German suppliers as the basis for their new energy-efficient homes (Figure 22). Energetikhaus 100 contractor started to work on solar energy in buildings with the collaboration of Soli fer Solardach and the University of Freiberg, with the objective of achieving 100% Solar houses [57]. The first house which was built in 2006 is reported to have a combined domestic hot water (DHW) and space heating solar fraction of 95% through the use of 69 m² of solar collectors on the south facing roof in combination with a 28 m³ buffer storage tank [58]. The other company Promassivhaus [59], which is a partnership of 50 construction companies, offers five different variants of dwelling all of which have a combined solar fraction in excess of 50%.

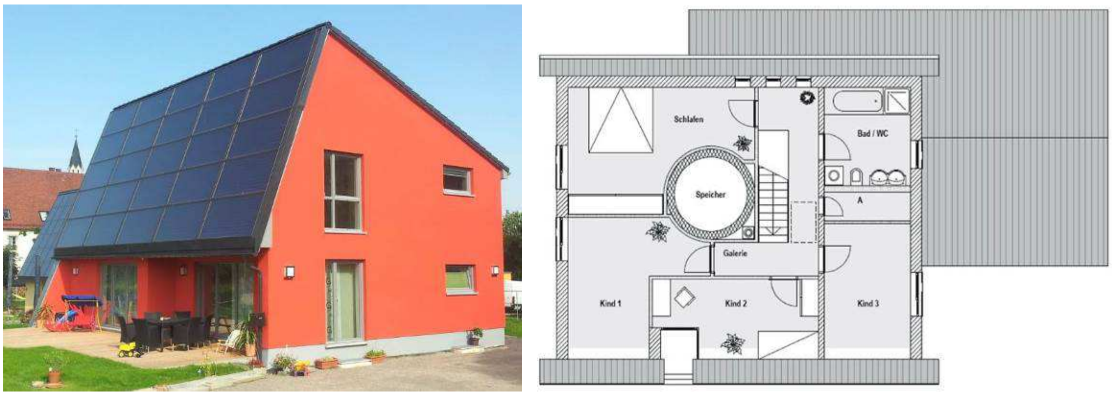


Figure 22. Left, Energetikhaus 100 showing Solar panels. Right, location of tank ("Speicher") within Energetikhaus 100 [57].

An analysis of a building integrated sensible seasonal thermal energy store has been conducted by Simons and Firth [60]. The apartment building is located in a lowland region of the Canton of Berne in Switzerland. The STES was designed and built prior to construction of the apartment building which was constructed to the Minergie-P standard.

As it can be seen from Figure 23, the STES consists predominantly of two components: the seasonal thermal energy storage vessel of volume 205 m^3 (which is partially underground) and the flat plate solar collector of 276 m^2. The STES vessel is an insulated mild steel cylinder containing steel heat exchanger coils in addition to three stainless steel boilers which are used to heat the potable DHW. The three boilers are placed at different levels within the storage vessel, only one of which is used at any one time. The stored water cools from the bottom and, once the water temperature drops below a certain threshold, the higher boiler is used to achieve the desired temperature. The flat plate solar collectors form the whole south-facing side of the roof and are specifically designed to function as the roofing cover. Only the glass and rubber seals are externally exposed which allows the structural elements to be constructed of timber.

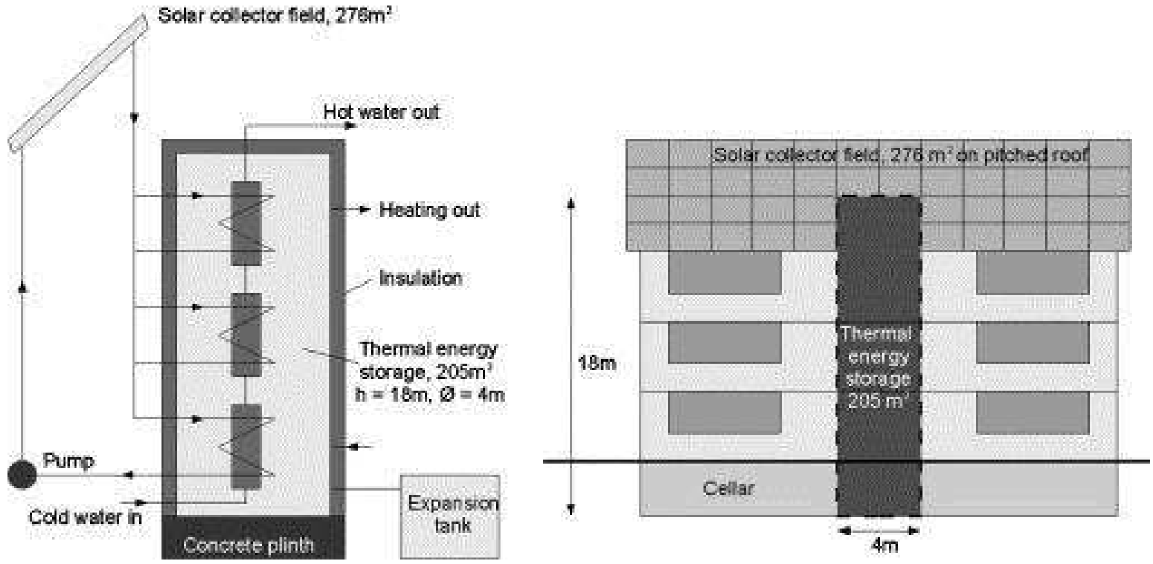


Figure 23. Main components of Berne STES and location and size relative to the apartment building [60]. Reprinted from, Energy and Buildings, 43(6), A. Simons, S.K. Firth, Life-cycle assessment of a 100% solar fraction thermal supply to a European apartment building using water-based sensible heat storage, 1231-40, June 2011, with permission from Elsevier.

The STES has been shown to be successful in meeting the heating and hot water demands throughout the year. In respect to energy demand, the analysis undertaken by Simons and Firth has shown that over a relatively short lifetime of 40 years, the total non-renewable primary energy used in producing, operating and disposing of the STES is far lower than any of the other heating systems used in the comparison, hence according to this aspect the initial investment is justified.

Using a range of lifetime scenarios it was found that the solar thermal system displays potentially significant advantages over the other systems considered (air-source heat-pump, ground-source heat pump, natural gas furnace, oil furnace and a wood-pellet furnace) in terms of reductions for purchased primary energy (from 84 to 93%) and reductions in GHG emissions (from 59 to 97%). However, the solar thermal system has been shown to have a higher demand for resources (a factor of almost 38 compared with the natural gas system considered).

Northern Maritime Europe

In Temperate Maritime Climates, a number of projects have been focused on the advantages afforded by integrating solar thermal systems and storage water tanks into the building concept. In Ireland, a building (Figure 24) constructed according to the passive house standard which is located in the West coast of the country, has an integrated underground seasonal thermal energy store and has been monitored [61].

Figure 24. Passive House showing Solar panels and location of STES (under greenhouse) [61].

The 215 m^2 (treated floor area) detached Passivhaus has an STES system integrated comprising a 10.6 m^2 evacuated tube solar array, 300 L Domestic Hot Water (DHW) tank, 23 m^3 aqueous STES (Figure 25) and combined under floor and Heat Recovery and Ventilation (HRV) space heating system.

Figure 25. Application of 600 mm EPS insulation to STES [61].

Solar energy is first used to meet the DHW requirements, and then the space heating requirements (either via the wet underfloor heating system or via the heat exchanger (HX) in the HRV system). Any surplus solar heat is diverted to the STES. The system has been shown to supply 70% of the combined DHW and space heating demand over a monitored season (Figure 26) [61], which is close to the maximum theoretical maximum determined by TRNSYS modelling [62]. Similar to the Simons and Firth study, a life cycle carbon analysis demonstrated that there was an advantage in installing the Seasonal Thermal Energy Store, as the annual energy savings of the overall installation greater than 4.5 times the annualised embodied energy [62].

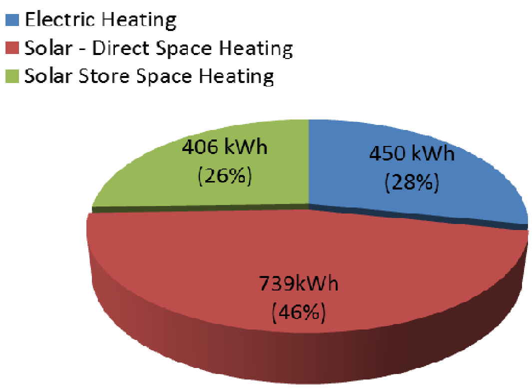


Figure 26. Breakdown of solar and electric space heating over monitored season [61].

Scandinavian Homes, a manufacturer of low-energy houses is participating in the FP 7 EINSTEIN project [54] as it has recently renovated a building and has installed a STES in the basement of a new building (Figure 27).

Figure 27. Solar panels on roof of Renovated building [54].

The STES comprises a 50 m² solar array comprises 10 panels of 1.8 m² aperture (totalling 18 m²) of evacuated tube collectors and 16 panels of 2 m² aperture, (totalling 32 m²) of flat plate collectors. A 3300 L buffer tank located in building one is logically divided (although not physically) in two based on thermal stratification considerations (Figure 28). The solar collectors supply heat to the heat exchanger coil in the middle of the buffer tank 1 or heat exchanger coil at the bottom of the buffer tank 2.

In addition a STES has been installed in the basement of a new building on the site. Once the heat injection surpasses the buffer tank requirements, heat excess is fed to "tank 3". The STES supplies heat to the new building. Monitoring of the installation commenced in 2013 and will determine the solar fraction from the overall STES.

Figure 28. Application of insulation to STES which is located in the basement [54].

Table 4. Main properties that enclose the systems reviewed

		Reference	Location	Climatic conditions[1]	Application	System description	Building type	Charge/Discharge	
Building core activation	Ceiling/floor	Chen et al [11,12]	Eastman, Québec, Canada	Snow, Fully humid, Warm summer	Heating/ Cooling	Ventilated concrete slab coupled with BIPV/T system, air based	Light weight prefabricated	Active	Passive
		Navarro et al [13]	Puigverd de Lleida, Spain	Warm temperate, Summer dry, Hot summer	Heating/ Cooling	Concrete slab with macro-encapsulated PCM, air based	Alveolar brick	Active	Active/ Passive
		Barton et al. [14]	-	Numerical model	Cooling	Ventilated concrete slab, air based	-	Active	Active/ Passive
		Jin and Zhang [16]	-	Numerical model	Heating/ Cooling	Radiant floor with PCM, water based	-	Active	Passive
		Pomianowski et al [17]	-	Numerical model	Cooling	Concrete slab with water pipes and PCM concrete layer, water based	-	Active	Passive
	Wall	Fraisse et al [19]	Mâcon, France	Numerical model (warm temperate, fully humid, warm summer)	Heating/ Cooling	Heavy internal wall with an integrated solar collector, air based	Timber frame house	Active	Active/ Passive
Suspended ceilings		Roulet et al [21]	-	-	Heating/ Cooling	Radiant panel, water based	-	Active	Passive
		Koschenz and Lehmann [22]	-	Laboratory facility and numerical model	Cooling	Gypsum panel with microencapsulated PCM and capillary tubes, water based	-	Active	Passive
lation syste	Pipes /ducts	Turnpenny et al. [23-25]	Nottingham, United Kingdom	Laboratory facility	Cooling	Heat pipes embedded in a PCM unit, air based	-	Active	Passive

		Daneshill House Refurbishment [26]	Stevenage, United Kingdom	Warm temperate, Fully humid, Warm summer	Cooling	Suspended ceiling in contact with concrete slab and with PCM, air based	Office building	Active	Active
		Yanbing et al [27]	Beijing, China	Snow, Winter dry, Hot summer	Cooling	Suspended ceiling with PCM macro-encapsulated in flat plates, air based	Brick-wall office building	Active	Active
		Stritih and Butala [28]	-	Laboratory facility	Cooling	Metal box with fins filled of PCM in suspended ceiling air based	-	Active	Active
	AHU	Monodraught Ltd. [29]	Sheffield, United Kingdom	Warm temperate, Fully humid, Warm summer	Cooling	Air handling unit with PCM heat exchanger, air based	Window facade office	Active	Active
External solar facade	Sensible heat storage	Fallahi et al. [31]	-	Numerical model, Laboratory facility	Heating/ Cooling	Thermal mass combination with Double Skin Façade, air based	-	Active/ Passive	Active/ Passive
	Latent heat storage	Costa et al. [32]	-	Three European climates (Southern, Central and Northern climates)	Cooling	Ventilated double skin facade, air based	-	Active	Active
		De Gracia et al. [33]	Puigverd de Lleida, Spain	Warm temperate, Summer dry, Hot summer	Heating/ Cooling	Ventilated facade with macro-encapsulated PCM inside the air chamber, air based	Alveolar brick	Active/ Passive	Active/ Passive
		Diarce et al. [34]	Vitoria-Gasteiz, Spain	Warm temperate, Fully humid, Warm summer	Heating/ Cooling	Ventilated facade with macro-encapsulated PCM as external layer, air based	Brick based walls	Active	Active

Thermal solar collectors		Eames and Griffiths [36], Griffiths et al. [37], Huang et al. [38]	-	Numerical model	DHW	Thermal energy storage unit with PCM integrated in a thermal solar collector	-	Active	Active
Thermal management of PV systems		Huang et al. [43-45]	-	Numerical model, Laboratory facility	Thermal management PV	Building integrated photovoltaic panel with PCM storage vessel behind the PV panel	-	Passive	Passive
		Hasan et al. [46,47]	Dublin, Ireland and Vehari, Pakistan	Warm temperate, Fully humid, Warm summer/ Arid, Desert, Hot arid	Thermal management PV	Building integrated photovoltaic panel with PCM storage vessel behind the PV panel	-	Passive	Passive
		Japs et al. [48]	Paderborn, Germany	Warm temperate, Fully humid, Warm summer	Thermal management PV	Building integrated photovoltaic panel with PCM bags behind the PV panel	-	Passive	Passive
		Jie et al. [49]	Hefei, China	Warm temperate, Fully humid, Hot summer	Heating, electricity	Trombe Wall combined with PV panel	Brick based walls	Active	Active
Heat storage water tanks	Building	Sonnenhaus-Institu [52]	Germany	Warm temperate, Fully humid, Warm summer	Heating, DHW	Water storage tank from solar systems	-	Active	Active/ Passive
		Jenni Energietechnik Inc. [56] Simons and Firth [60]	Switzerland	Warm temperate, Fully humid, Warm summer	Heating, DHW	Water storage tank from solar systems	-	Active	Active/ Passive

		Energetikhaus 100 [57-58] ProMassivhaus [59]	Germany	Warm temperate, Fully humid, Warm summer	Heating, DHW	Water storage tank from solar systems	-	Active	Active/ Passive
	Ground integrated	Clarke et al. [62] and Colclough [61,63]	Ireland	Warm temperate, Fully humid, Warm summer	Heating, DHW	Integrated underground seasonal thermal energy storage tank	Light weight builging	Active	Active

[1] Climate conditions following the Köppen-Geiger climate classification [64].

10. Conclusions

Thermal energy storage (TES) is considered a promising principle that enhances the efficiency of renewable energies through the reduction of the supply and production gap. There are many studies in the literature where TES has been applied on building envelopes as passive system, in the HVAC systems or in solar thermal systems. But when designing building systems the location where the system will be installed and its volume has to be taken into account. Although current TES technologies developed by researchers demonstrated significant potential, there is a lack of knowledge concerning their functional and architectural building integration. Since the main objective is the implementation of TES in different components of the building to reduce its energy consumption, the incorporation of these systems should be as helpful as possible for the architects and engineers involved with design.

The integration of thermal storage systems in buildings is considered a relevant aspect to take into account in building designs, in order to overcome the problems of space availability for installations in buildings. Some systems can be found in the literature which show that building integration of TES systems is not only possible but already done today.

Active systems require an effort in their design to achieve an adequate incorporation, taking into account climatic conditions, aesthetical and functional requirements. In this paper a summary and classification on building active integration has been carried out.

Building core activation is demonstrated to be an interesting technology for new constructions domestic, public or office buildings. However, ceiling and floor activation components are considered better than wall activation as they are usually exposed and wall surfaces are usually used for shelving, cupboards, or other furniture. Moreover, few commercial products have been developed as prefabricated components with the implementation of water pipes in a concrete slab or air ducts system inside a hollow concrete slab.

Since, energetic regulations in building sector are becoming stricter, old buildings need retrofitting to accomplish the new energy efficiency standards so implementation of energy saving actions must be undertaken. Suspended ceiling products such as radiant panels or thermal activated gypsum panels, which were experimentally tested with successful results, may be possible solutions for building energetic refurbishment.

Office and public buildings have huge potential on implementing thermal energy storage in double skin facades and in ventilation systems either air ducts or air handling units. Commercial systems which incorporate phase change materials in the AHU are currently marketed for use in buildings. Other active systems with TES reviewed have included the incorporation of PCM in BIPV panels where BIPV-PCM systems have demonstrated and increase in PV performance due to the thermal management functionality of the PCM through excess heat storage.

Some seasonal thermal water tanks coupled to solar systems have been installed within the last decade in central Europe countries to cover domestic hot water and heating supply.. The main issue to highlight is the architectural integration of the huge water storage tanks, for example making them a feature of stairwells in single houses and small apartments building. Moreover, underground integration of seasonal thermal storage water tanks was also presented. As seasonal water tanks integration requires lot of space for their integration it has limited potential.

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